EXECUTIVE SUMMARY

Background

Due to the perceived occurrence of high-intensity storms more frequently than expected, the Michigan Department of Transportation (MDOT) has deemed it necessary to update the regional rainfall intensity-duration-frequency (IDF) estimates for the State. Recently, a nine-state study has shown that stations in the Midwest, including those in Michigan, have measured an unexpected number of heavy rainfall events in recent years (Angel and Huff, 1997). For Michigan, it was found that the 24-hour, 100-year value was exceeded 71 times, while only 21 exceedances were expected. In general, it is recommended that rainfall frequency studies be updated on a regular basis for maximum reliability.

Objectives

The overall objective of this study is to revise Michigan's rainfall IDF estimates by: 1) obtaining and screening the most up-to-date gaged rainfall data; 2) delineating homogeneous regions for a regional frequency analysis; 3) fitting an appropriate 3-parameter probability distribution to the observed data; 4) estimating the distribution parameters; 5) spatially interpolating a site-specific scale factor to account for regional variability; and 6) presenting revised IDF estimates in tabular and graphical forms. Additionally, the development of an interactive geographical information system (GIS) model for display and retrieval of site-specific rainfall IDF estimates is discussed. Rainfall intensity estimates are determined for each of eleven durations (5, 10, 15, 30, 60,

120, 180, 360, 720, 1080, and 1440 minutes) and six recurrence intervals (2, 5, 10, 25, 50 and 100 years).

Data Used

This study utilizes data from 76 hourly and 152 daily rainfall-recording stations throughout Michigan, along with 81 Southeast Michigan Council of Governments (SEMCOG) short duration rainfall-recording stations located in 5 counties in and around the Detroit area (see Figure 3.1). Annual maximum series (AMS) data, containing the largest value in each year, were compiled from hourly and daily data. (AMS data were not available for the SEMCOG recording stations.) Partial duration series (PDS) series data, containing a certain number of the largest values regardless of the year in which they were recorded, were compiled for all durations. In this study, each PDS series contains the $2N$ highest rainfall intensity values, where N is the number of years of record.

In the analysis, rainfall intensities for 5 to 30 minutes were based on the SEMCOG data, intensities for durations from 1 to 18 hours were derived from hourly records, and 24-hour were derived from daily records. SEMCOG recording stations have record lengths ranging from 16 to 38 years, with an average record length of 30 years (through 1999). The hourly recording stations have record lengths ranging from 18 to 49 years, with an average record of 41 years (through 1996). The daily recording stations have record lengths ranging from 21 to 117 years, with an average record of 63 years (through 1996).

Procedure

In contrast to a traditional at-site frequency analysis using the method of moments to estimate distribution parameters, this study applies a regional frequency analysis approach based on *L*-moments. In a regional frequency analysis, regional information is used to increase the reliability of rainfall IDF estimates at any particular site (Hosking and Wallis, 1997). One limitation is that the procedure assumes that sites from a homogeneous region have an identical frequency distribution apart from a site-specific scaling factor.

L-moments are defined as expectations of certain linear combinations of order statistics (Hosking, 1990). They are analogous to conventional moments with measures of location (mean), scale (standard deviation), and shape (skewness and kurtosis). Because *L*-moments are linear combinations of the ranked observations and do not involve squaring or cubing the observations as is done for the conventional method of moments estimators, they are generally more robust and less sensitive to outliers.

The procedure followed in this study is outlined below (Hosking and Wallis, 1997). The main steps are to screen the data, identify homogeneous regions, chose a frequency distribution, estimate the parameters of the chosen distribution, and compute quantile estimates.

(1) Screening the Data. The first step in any statistical investigation is to check that the data are suited for the analysis. Tests for gross outliers, inconsistencies, shifts, and trends are ways to check the appropriateness of the data. Additionally, Hosking and Wallis (1997) present a discordancy measure based on the *L*-moments of the sites' data. The discordancy measure is a single statistic based on the difference between

the L-moment ratios of a site and the average L-moment ratios of a group of similar sites. This statistic can also be used to identify erroneous data.

*(2) Identifying Homogeneous Regions***.** The purpose of this step is to form groups of stations that satisfy the homogeneity condition, i.e., stations with frequency distributions that are identical apart from a station-specific scale factor. Stations can be grouped subjectively by site characteristics (i.e., latitude, longitude, elevation, and mean annual precipitation). For example, Schaefer (1990) defined homogeneous regions based on mean annual precipitation for a regional frequency analysis study of annual maximum precipitation in the State of Washington. Stations can also be grouped objectively using cluster analysis procedures. Cluster analysis is a multivariate statistical analysis procedure for partitioning a data set into groups. The procedure involves assigning a data vector to each site. Sites are then divided into groups based on the similarity of their data vectors. The data vectors can consist of site statistics, site characteristics, or some combination of both. Hosking and Wallis (1997) recommend basing the regionalization of sites on site characteristics alone.

*(3) Choosing a Frequency Distribution***.** In regional frequency analysis, a single frequency distribution is fit to the data from several sites in a homogeneous region. Because the "true" distribution of rainfall is not known, a distribution must be chosen that not only provides a good fit to the data, but will also yield reliable and robust and quantile estimates for each site in the region. The candidate three-parameter distributions considered for quantile estimation in this study were the Generalized Logistic (GLO), the Generalized Extreme Value (GEV), the Lognormal (LN3), the Pearson Type III (PE3), and the Generalized Pareto (GPA). To aid in selection of an

appropriate distribution, Hosking and Wallis (1997) introduce another statistic called the *Z*-statistic. The *Z*-statistic is a goodness-of-fit measure for three-parameter distributions which measures how well the theoretical *L*-kurtosis of the fitted distribution matches the regional average *L*-kurtosis of the observed data.

(4) *Parameter Estimation***.** To estimate a chosen distribution's parameters and obtain quantile estimates, the regional *L*-moment algorithm is used (Hosking and Wallis, 1997). This procedure involves fitting the chosen distribution using the method of *L*-moments; its parameters are estimated by equating the population *L*-moments of the distribution to the sample *L*-moments derived from the observed data. Next, sample *L*-moment ratios from each site in a homogeneous region are weighted according to record length and combined to give regional average *L*-moment ratios. Hosking and Wallis (1997) found that averaging *L*-moment ratios rather than the *L*-moments themselves yields more accurate quantile estimates in all cases examined. Next, the regional mean is set equal to 1, and regional quantile estimates are derived. Final quantile estimates are obtained by multiplying the regional quantile estimate by the index flood, which for this study is the at-site estimate of the mean.

(5) *Determination of Rainfall IDF Estimates at Ungaged Sites***.** To obtain rainfall IDF estimates at ungaged sites, the regional quantile estimates derived from data at gaged sites within a region are interpolated to all ungaged sites in that region. Specifically, the index flood values (at-site means) are spatially interpolated over the State using geostatistical methods. This allows for rainfall IDF estimates for durations of 1, 2, 3, 6, 12, 18 and 24 hours to be determined for any location in the State of Michigan. For durations of less than 1 hour, a procedure was devised to extrapolate the results

obtained for the SEMCOG gages. The procedure assumes that the ratio of *N*-minute to 60-minute rainfall intensity is constant throughout the State.

Results

In screening the data, trend analyses were first conducted. Since analysis of the daily AMS data indicated a positive trend over time, it is recognized that some adjustment may be necessary to put greater weight on the more recent daily rainfall events. Little evidence of such trends was identified in the hourly AMS data, however; therefore no adjustments to results derived from hourly observations are deemed necessary. A negative trend over time was actually indicated in the short duration (10- and 30-minute) data, so no adjustments are recommended.

A temporal analysis of the daily PDS data revealed significant increases in the frequency of heavy rainfall in Michigan over a 70-year period (1927-96). In light of this, quantile estimates derived from the 1960-96 period were compared with those derived from the full period of record. No significant differences were found. As a result, no measures are recommended to account for the trend in the daily PDS data. To identify trends in the hourly PDS data, a quantile comparison was again conducted. For the 1- and 12-hour durations, quantile estimates derived from the 1974-96 period were compared with those derived from the full period of record. Significant differences were observed only at the 50- and 100-year recurrence intervals for the 12-hour duration. Taking into account sampling variability, and the fact that there were no significant differences in the daily and 1-hour quantile comparisons, these differences are not accounted for in rainfall IDF estimation. For the 10- and 30-minute durations, the quantile estimates derived from the 1980-99 period were found to be lower than those from the full period of record. These differences are not accounted for in the rainfall IDF estimation as sampling variability over the relatively short period of record might account for this difference.

To identify homogeneous regions, the correlation between rainfall intensity and site characteristics that are commonly associated with heavy rainfall was evaluated. Little correlation was found between rainfall intensity and distance from the closest Great Lake, elevation, and mean annual precipitation. In other words, sampling variability obscures whatever correlation exists. In light of these findings, and the fact that the homogeneity criteria were satisfied with all sites lumped into one region, it was deemed that the State potentially could be treated as one homogeneous region.

To examine the possible adverse effects of treating the State as one region, three other regionalization schemes were evaluated and the resulting quantile estimates compared. Cluster analysis procedures (Hosking and Wallis, 1997) were used to aid in identifying two or three homogeneous regions within the State, with clusters based on the following site characteristics: latitude, longitude, elevation, and mean annual precipitation. Regional quantile estimates were then compared by dividing those derived from the candidate regions by the quantile estimates derived with the State as one region. Differences were deemed to be insignificant for the purposes of this study, so the results derived for the State as one region are recommended.

Consequently, the annual maximum series (AMS) and partial duration series (PDS) results were compiled using the index flood regional frequency analysis procedure outlined by Hosking and Wallis (1997), with the State considered one homogeneous region. Discordancy, heterogeneity and goodness-of-fit measures for AMS and PDS data were evaluated. The GEV distribution was found to provide the best fit for the AMS data for durations greater than one hour, while the GPA distribution provided the best fit for the PDS data for all durations.

Mathematically, the PDS/GPA model regional quantile estimates are slightly larger than the AMS/GEV quantiles regardless of duration and recurrence interval. This is because the PDS/GPA quantiles are based on more frequent storm events ($F = 1\text{-}1/\lambda T$, with $\lambda = 2$) than are the AMS/GEV quantiles ($F = 1\text{-}1/T$). Compensating for this mathematically, the PDS index floods (at-site means) tend to be lower than the corresponding means derived from the AMS data, since the PDS means are computed using the $2N$ highest rainfall intensity values, where N is the record length in years. Nonetheless, the AMS results appeared to be slightly higher in magnitude than the PDS results, while the PDS values showed slightly more north-south variation. The small differences in magnitude are easily attributed an empirical factor (1.136) applied to convert the 2-year AMS values to PDS values.

For practical purposes, the AMS/GEV and PDS/GPA models both provide rainfall IDF estimates that are similar in magnitude and variation across the State. Because estimates derived from AMS data rely on empirical factors to convert them to desirable PDS results for shorter recurrence intervals, it is recommended that estimates derived directly from the PDS data be used for the 2-, 5- and 10-year recurrence intervals. Since differences between the two series are negligible for recurrence intervals greater than 10-years, AMS results are recommended for the 25-, 50- and 100-year recurrence intervals for durations greater than and equal to 1-hour. (These AMS results also account for the positive trend detected in the daily rainfall data for these recurrence intervals.) Since AMS data was not available for the SEMCOG stations, PDS values must be used for all recurrence intervals for the short durations (less than 1 hour).

Final recommended IDF values for each of the 10 climatic sections in Michigan are summarized in tabular form in Appendix B and in graphical form (isopluvial maps) in Appendix C and on the accompanying CD. These results are compared to the results of previous studies and to the design IDF values currently used by MDOT. Additional verification of the results is accomplished by a “real data check,” in which the number of observed exceedances is compared to the number that would be expected statistically over the period of record.

The results derived in this study are first compared to *Bulletin 71*, *Rainfall Frequency Atlas of the Midwest* (Huff and Angel, 1992), which provided IDF estimates for nine States in the Midwest (including Michigan) for 1-hour to 10-day durations and for recurrence intervals of 2 months to 100 years. For the 1-hour, 2-year storm, results are very similar, with noticeable discrepancies in rainfall depth occurring only in the southwest portion of the Upper Peninsula and the southwest portion of the Lower Peninsula–this study’s results are lower by approximately 0.14 and 0.12 inches, respectively. Discrepancies in results are more pronounced for the 1-hour, 100-year storm, with this study’s results being 0.20 to 0.80 inches lower across the State than the values given *Bulletin 71*. Furthermore, the results from *Bulletin 71* show a variation in rainfall depths of 1.5 inches across the State, while this study’s results show depths varying by less than 0.50 inches. These discrepancies can be explained by differences in the data and methodology used. For instance, the results in *Bulletin 71* are based on rainfall data collected at 46 daily recording stations, and duration-specific conversion factors were applied to the 24-hour estimates to obtain 1-hour rainfall depths. Furthermore, Huff and Angel (1992) performed an at-site analysis and did not assume that data fit a specific probability distribution, in contrast to the regional frequency analysis done in this study.

Results presented herein are also compared to those given in *Rainfall Frequency for Michigan* (Sorrell and Hamilton, 1990), which updated *TP-40* 24-hour rainfall values for recurrence intervals of 2 to 100 years. For the 24-hour, 2-year storm, results derived herein are within ±0.15 inches of *Bulletin 71* results throughout the State, but are about 0.20 inches lower across the State than those derived by Sorrell and Hamilton (1990). All three sets of results show similar north-south variation in IDF values. For the 24-hour, 100-year storm, results from this study are comparable to those in *Bulletin 71*. (with differences in the northern Upper Peninsula and the southeastern corner of the Lower Peninsula), but they are notably higher than the values given by Sorrell and Hamilton (1990) for the northern parts of the State. These discrepancies are primarily attributed to differences in methodologies. In contrast to the regional frequency analysis with three-parameter distributions and *L*-moment estimators applied herein, Sorrell and Hamilton (1990) derived at-site IDF estimates using the two-parameter Gumbel distribution and method-of-moments estimators.

Finally, revised IDF estimates are compared to the values currently used for design, as given in the MDOT *Road Design Manual*. It is found that current MDOT estimates are significantly larger than those developed in this study. For instance, for 1-hour storms, current MDOT estimates of 10-year rainfall depths now appear to be closer to 50-year depths. Because it is unclear how the current MDOT IDF estimates were derived, based on adjustments to values derived in *TP-25* and *TP-40*, it is difficult to account for these discrepancies. Nonetheless, the verification of the revised IDF estimates indicates that the values lead the approximately the number of exceedances that would be expected statistically over the period of record. Thus, it appears that structures designed using the current MDOT IDF estimates are safe and reliable structures, but are possibly over-designed.